



ESTIMATION OF WING WEIGHT IN CONCEPTUAL DESIGN PHASE FOR TACTICAL UNMANNED AERIAL VEHICLES

Abdulkhkim Muhammad Essari

Department of Mechanical and Industrial Engineering, Elmergib University,
Alkhoms – Libya
hakimsari@yahoo.com

Abstract

New formula for wing weight estimation, in conceptual design phase is derived for a tactical unmanned aerial vehicle (TUAV). Formula is derived by analyzing existing UAVs of the weighs from 100 to 500 kg, and which have similar characteristics. The materials suggested for UAV weight design are aluminum alloys and aluminum based composite materials. Software tools are developed in Matlab to facilitate takeoff and component weight calculations. The least square method is applied to analyze statistical data in order to develop trend functions which correlate TUAVs empty weight and takeoff weight. Existing formulas, developed for general aviation, for wing and takeoff weight estimations are applied to TUAV and promising one are selected and adjusted to TUAV conceptual design phase. Wing weight is related to geometrical parameters, maximum speed, and takeoff weight of the TUAVs. All existing and newly developed formulas are applied to typical TUAV example to validate it applicability.

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1. Introduction:

UAV's are defined as aircraft which flies without pilot inside it. It can be released into the air in several ways such as ordinary runway, by hand, by launcher, by rocket, from bigger airplane, or any other convenient mean. UAV sizes start from insect size to thousands of kilograms according to its mission, altitude, endurance, range, and payload carried. Tracking and controlling of the UAV's are done automatically or by wireless connections. It also can fly fully autonomously by computer programmed mission, starting from the takeoff moment until it returns controlled all time by computers inside it [1]. Because UAVs have high-aspect-ratio wings and fly in low-density conditions, often at low speeds; airflow is characterized by low Reynolds numbers. Aerodynamic properties of such flying object are significantly different from properties of general aviation aircrafts or ultra-light aircrafts. New category of flying vehicles need extensive research in low Reynolds number flight regime, searching for shapes of sufficiently high lift coefficients and reasonably low sensitivity to flow separation. The first sizing of the wing was done using the results of the parametric analysis and its design was a highly iterative process. The main design driver was to minimize the weight consideration, which led to some compromises.

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Models of conventional tactical UAVs weights between 100 to 500 kg are chosen for wing weight estimation. The parameters values of these UAVs are input to Matlab program to get the result on chart; the results are evaluated and compared with the results of calculated equations for UAV weights 220 kg as takeoff weight. Wing weight represents about 17-27% of the empty weight [2].

Since conceptual design phase cost least, it is wise to perform it thoroughly and to postpone crucial decisions as late as possible since all subsequent phases are continuation of this phase. This will increase the cost of this phase but since its share in total cost is usually less than 5% increase is not significant, but can reduce significantly the cost of subsequent phases. It cannot be stressed enough that outcome of the conceptual design phase greatly depend on initial weight estimation of the UAV. This work will contribute to this problem by deriving equation for weight estimation.

2. Materials and Methods:

Methods of weight estimation are experimented for number of various kinds of TUAVs.

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2.1 Raymer method:

General aviation aircrafts equation for wing weight estimation from

Raymer: [3]
$$W_w = 0.036 \times S_w^{0.758} \times W_{fw}^{0.0035} \times \left(\frac{A}{\cos^2 \Lambda} \right)^{0.6} \times q^{0.006} \times \lambda^{0.04} \times \left(\frac{100 \times t/c}{\cos \Lambda} \right)^{-0.3} \times (N \times W_{dg})^{0.49}$$

W_w – wing weight, S_w – exposed wing area, W_{fw} – fuel weight, A – aspect ratio, λ – taper ratio, q – dynamic pressure, Λ – sweep angle at 25% MAC, t/c – wing thickness cord ratio, N – ultimate load factor, W_{dg} – design gross weight.

All of the dimension parameters of the wing geometry are presented in Raymer wing weight fraction (W_w/W_o) equation, beside some other parameters such as; design gross weight, ultimate load factor, fuel weight, and dynamic pressure. Raymer equation is mostly affected by values of takeoff weight and planform wing area of the aircraft.

From figure (1), the results of wing weight fraction (W_w/W_o) of Raymer equation according to the fitting line range between 10% at 100 kg and 12.2 % at 500 kg takeoff weight.

For 220 kg takeoff weight, wing weight is equal to 33.85 kg which represents 15.38 %

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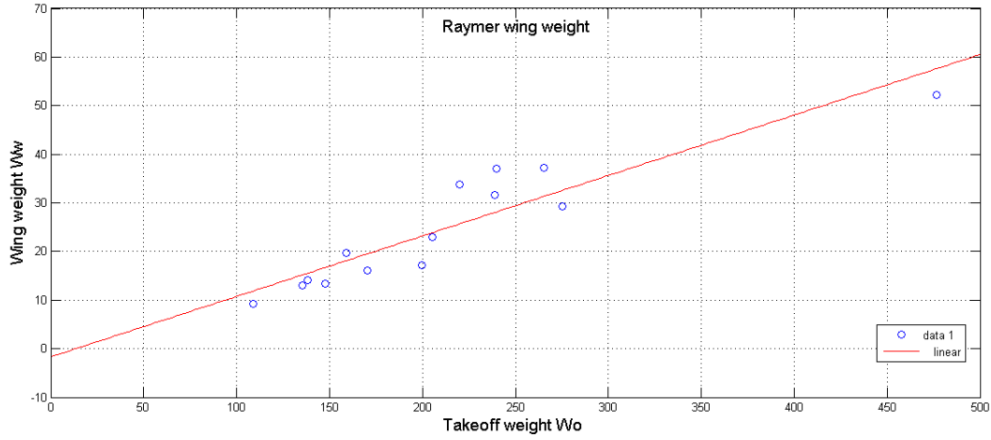


Figure (1) Raymer wing weight estimation

By substitution in Raymer equation for parameters values that we got for aircraft which has takeoff weight value 220 kg, the result is as follow:

$$W_w = 0.036 \times 56.7^{0.758} \times 170^{0.0035} \times \left(\frac{8}{\cos^2 0}\right)^{0.6} \times 16.4^{0.006} \times 1^{0.04} \times \left(\frac{100 \times 0.15}{\cos 0}\right)^{-0.3} \times (9 \times 485)^{0.49}$$

$$W_w = 74.6 \text{ lb} = 33.85 \text{ kg}$$

Comparing the outcome of the equation and the value of wing weight that we got from the figure, it is clear that there is approximately same.

2.2 Usaf method:

Usaf general aviation aircrafts equation for wing weight estimation: [4]

$$W_w = 96.948 \times \left(\left(\frac{W_o \times N_z}{10^5}\right)^{0.65} \times \left(\frac{A}{\cos \Lambda}\right)^{0.57} \times \frac{S_w^{0.61}}{100} \times \left(\frac{1 + \lambda}{2 \times t/c}\right)^{0.36} \times \left(1 + \frac{V}{500}\right)^{0.993}\right)$$

W_o – takeoff weight, N_z – ultimate load factor, A – aspect ratio, λ – taper ratio

S_w – Wing reference area, t/c – thickness to wing ratio, V – maximum speed at sea level.

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In Usaf equation we can see that the parameters of the equation are moderately used, so that the equation outcome is not affected dramatically by changing any parameter individually. The equation basically depends upon the fixed number (96.948), we can see that clearly in figure (2). The fixed number is very big for this equation.

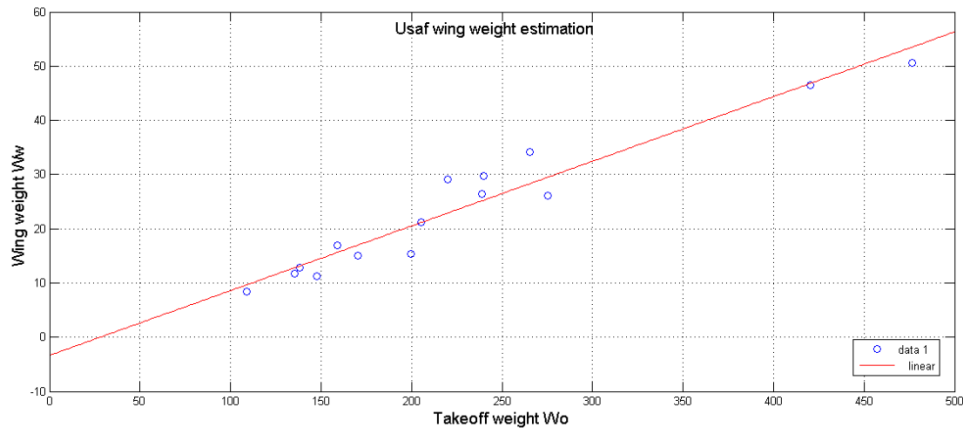


Figure (2) Usaf wing weight estimation

From Figure (2), the results of wing weight fraction (Ww/Wo) of Usaf equation according to the fitting line, range between 8% at 100 kg and 11.2 % at 500 kg takeoff weight. For 220 kg takeoff weight, wing weight is equal to 28.85 kg which represents 13.11 %

By substitution in Usaf equation for values that we got for aircraft which has takeoff value 220 kg, the result is as follow:

$$\begin{aligned}
 Ww &= 96.948 \times \left(\left(\frac{485 \times 9}{10^5} \right)^{0.65} \times \left(\frac{8}{\cos 0} \right)^{0.57} \times \frac{56.7^{0.61}}{100} \right. \\
 &\quad \left. \times \left(\frac{1+1}{2 \times 0.15} \right)^{0.36} \times \left(1 + \frac{108}{500} \right)^{0.5} \right)^{0.993} = \\
 Ww &= 63.6 \text{ lb} = 28.85 \text{ kg}
 \end{aligned}$$

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2.3 Kroo method:

Kroo equation for wing weight estimation: [5]

$$W_w = 4.22 \times S_{wg} + 1.642 \times 10^{-6} \left(\frac{N_{ul} \times b^3 \times (TOW \times ZFW)^{0.5} \times (1 + 2 \times \lambda)}{(t/c) \times \cos^2 \Lambda \times S_{wg} \times (1 + \lambda)} \right)$$

W_w – wing weight. S_{wg} – gross wing area, TOW- takeoff weight, ZFW – fuel weight

Λ_{ea} – sweep of the structural axis, λ – taper ratio, t/c – average airfoil thickness

N_{ul} – ultimate load factor, b – wing span.

The Wing weight estimation equation established by Kroo is fundamentally formed for big size aircrafts. This equation is dramatically controlled by gross wing area (S_w) parameter, beside some other parameters which has lesser extent effect such as ultimate load factor, wing span, takeoff weight, fuel weight, average airfoil thickness, taper ratio, and sweep of the structure axis.

By substitution in Kroo equation for parameters values that we got for aircraft weighs 220 kg as takeoff weight, the result is as follow:

$$W_w = 4.22 \times 56.7 + 1.642 \times 10^{-6} \left(\frac{9 \times 21.3^3 \times (485 \times 170)^{0.5} \times (1 + 2 \times 1)}{(0.15) \times \cos^2 0 \times 56.7 \times (1 + 1)} \right)$$

$$W_w = 246.5 \text{ lb} = 111.91 \text{ kg}$$

For 220 kg takeoff weight, wing weight is equal to 111.91 kg which represents 50.85 % of W_o .

The results of wing weight fraction (W_w/W_o) of the Kroo equation according to the fitting line, Figure (3), range between 52 % at 100 kg and 24 % at 500 kg takeoff weight.

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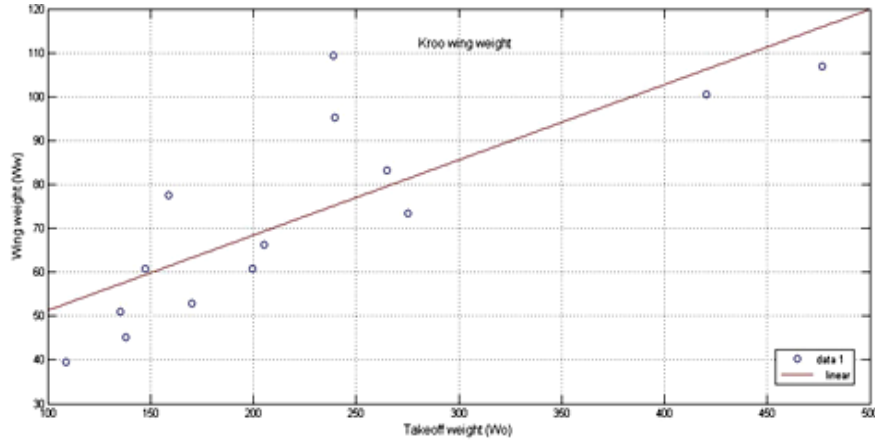


Figure (3) Kroo wing weight estimation

2.4 Torenbeek method:

This equation applies to light transport aircrafts with takeoff weights less than 5600 kg. (4),(8)

$$W_w = 0.00125 \times W_o \times \left(\frac{b}{\cos \Lambda} \right)^{0.75} \times \left(1 + 6.3 \times \frac{\cos \Lambda}{b} \right)^{0.5} \times N_z^{0.55} \times \left(\frac{b \times S_w}{t \times W_o \times \cos \Lambda} \right)^{0.3}$$

From Figure (4), fitting line indicates that the wing weight fraction for 100 kg is 8.5% and increased to reach 10.3% at 500 kg. For our aircraft which weighs 220 kg takeoff weight the wing weight fraction is 13.24 %.

By substitution in Torenbeek equation for parameters values that we got for aircraft which weighs 220 kg, the result is as follow:

$$W_w = 0.00125 \times W_o \times \left(\frac{21.3}{\cos 0} \right)^{0.75} \times \left(1 + 6.3 \times \frac{\cos 0}{21.3} \right)^{0.5} \times 9^{0.55} \times \left(\frac{21.3 \times 56.7}{0.4 \times 485 \times \cos 0} \right)^{0.3} = 29.13$$

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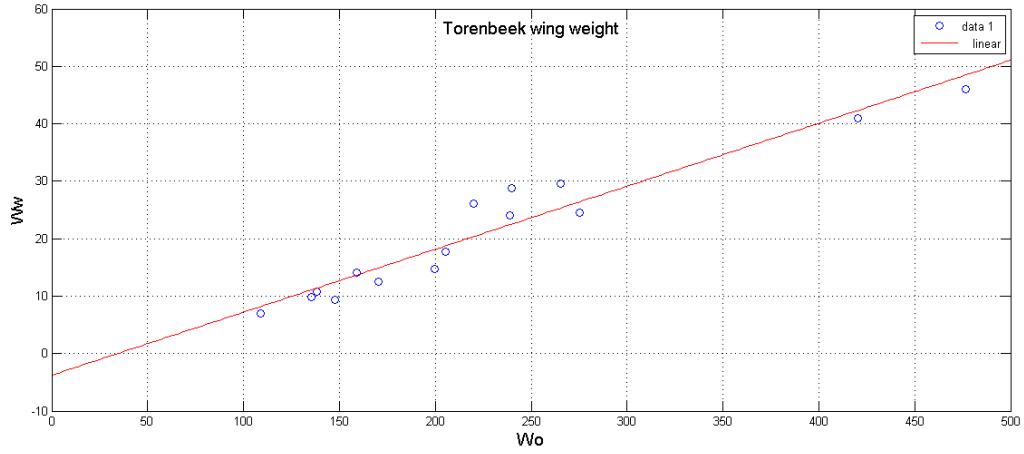


Figure (4) Torenbeek wing weight estimation

2.5 Jay Gundlach method:

The following wing weight equation is developed by Gerard for manned sailplanes: [6].

$$W_w = 0.0038 \times (N_z \times W_o)^{1.06} \times A^{0.38} \times S_w^{0.25} \times (1 + \lambda)^{0.21} \times (t/c)^{0.14}$$

N_z - the ultimate load factor, W_o – takeoff weight, A – aspect ratio, S_w - wing planform area, λ – taper ratio, t/c - thickness-to-chord ratio

From figure (5), the results of wing weight fraction (W_w/W_o) of Gerard equation according to the fitting line range between 8.5% at 100 kg and 17.6 % at 500 kg takeoff weight. For our aircraft which weighs 220 kg, wing weight is equal to 35.14 kg which represents 15.97 %.

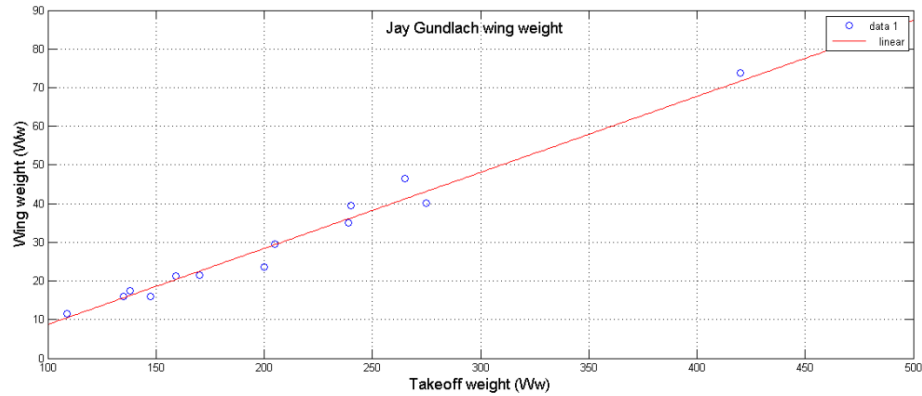


Figure (5) Jay Gundlach wing weight estimation

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By substitution in Gerard equation above for $W_o = 220$ kg and the other parameters we got before for wing area, aspect ratio, thickness to cord ratio, and taper ratio.

$$W_w = 0.0038 \times (9 \times 220)^{1.06} \times 8^{0.38} \times 5.27^{0.25} \times (1 + 1)^{0.21} \times (0.15)^{0.14} = 35.135 \text{ kg}$$

2.6 Kundu method:

Kundu equation is derived and modified from general equation published by SAWE: [7].

$$M_w = K (M_{dg} N_z)^{x1} S W^{x2} AR^{x3} (t/c)^{x4} (1 + \lambda)^{x5} (\cos \Lambda_{1/4})^{x6} (B/C)_t^{x7} S_{CS}^{x8}$$

$$W_w = 0.0215 \times (W_o \times N_z)^{0.48} \times S_w^{0.78} \times A \times (1 + \lambda)^{0.4} \times \frac{\left(1 - \frac{W_f}{W_o}\right)^{0.4}}{\cos \Lambda \times (t/c)^{0.4}} \text{ (Kundu equation)}$$

The results of wing weight fraction (W_w/W_o) of Kundu equation according to the fitting line range between 18% at 100 kg and 22 % at 500 kg takeoff weight.

By substitution in Kundu equation for takeoff weight and the other parameters we got before for our aircraft such as, wing area, aspect ratio, fuel fraction, thickness to cord ratio, taper ratio, and sweep angle, the result is as follow:

$$W_w = 0.0215 \times (220 \times 9)^{0.48} \times 5.27^{0.78} \times 8 \times (1 + 1)^{0.4} \times \frac{(1 - 0.23)^{0.4}}{\cos 0 \times (0.15)^{0.4}} = 60.9 \text{ kg}$$

Figure (6) shows Wing weight from Kundu which represents 27.7 % of W_o .

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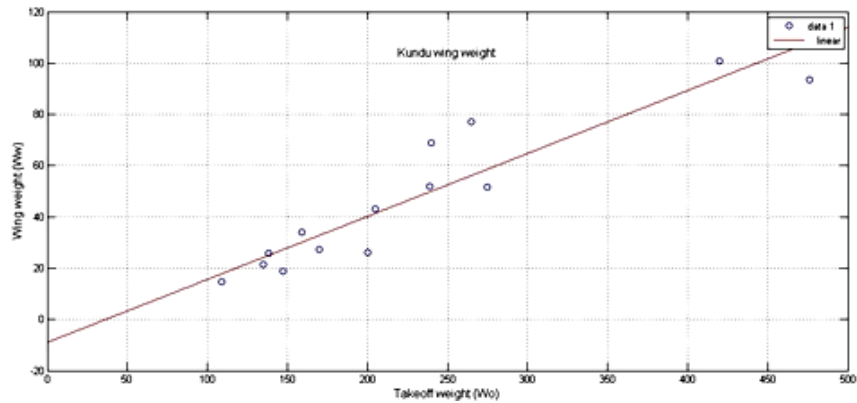


Figure (6) Kundu wing weight estimation

3. Results and Discussion:

In this part of research the methods are being to be discussed and analyzed.

3.1 Empty weight fraction:

First estimation of takeoff weight W_o for the previous characteristics is: $W_o = 220$ kg, and empty weight fraction is $W_e/W_o = 0.585$. Figure (7), which is equal to 128.7 Kg, the empty weight includes wing weight, empennage weight, fuselage weight, carriage weight, and engine group weight.

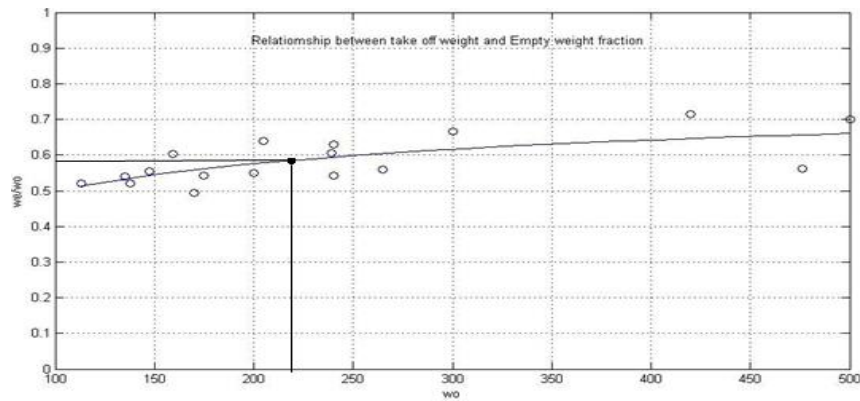


Figure (7) Empty weight fraction and takeoff weight relationship

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3.2 Equations Analysis:

Many formulas were used in this work to find the wing weight estimation and the results were shown on charts. Because of all these formulas are not established for unmanned aircrafts, so in some cases we see unreasonable and extreme results for wing weight estimation. But in some few cases we got reasonable results. Comparison of all the results that we got from the equations of previous methods for wing weight estimation of UAV having 220 kg takeoff weight, and the results extracted from the figures, we can see that the formulas of Raymer, Usaf, Torenbeek, Gundlach gave satisfied values of the estimated wing weight.

The wing weight represents about 17-27% of the empty weight [2].

Wing area in our case is relatively big compared to the aircraft empty weight because of low wing loading value, so we will consider the wing weight to be around 27%. We concluded from the foregoing that the Jay Gundlach formula which founded by Gerard for manned sailplanes or Raymer formula give the best results between all of the other formulas.

Usaf and Torenbeek formulas show acceptable results, but these results give value which are not enough for this big wing. Usaf wing weight is equal to 22.37% of the empty weight and Torenbeek wing weight is equal to 22.63%. Gundlach formula outcome is meet our request but the fitting line slope in Figure (8) shows a big difference between 8.5% at 100 kg and 17.6 % at 500 kg takeoff weight which make it unreliable. The result we got from Raymer formula is the best between the previous formulas. Raymer equation offers 33.85 kg for our aircraft wing weight, this equal to 26.3% of W_w/W_e . Raymer fitting line slope in figure (9) shows 9 % of

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Ww/Wo at 100 kg and 12.2 % at 500 kg. For 220 kg the Ww/Wo the wing weight fraction is 15.38% at 220 kg.

Jay Gundlach equation for sailplane:

$$W_w = 0.0038 \times (N_z \times W_o)^{1.06} \times A^{0.38} \times S_w^{0.25} \times (1 + \lambda)^{0.21} \times (t/c)^{0.14}$$

$$W_w = 0.0038 \times (9 \times 220)^{1.06} \times 8^{0.38} \times 5.27^{0.25} \times (1 + 1)^{0.21} \times (15)^{0.14} = 35.14 \text{ kg}$$

This weight represents 27.3% of the aircraft empty weight.

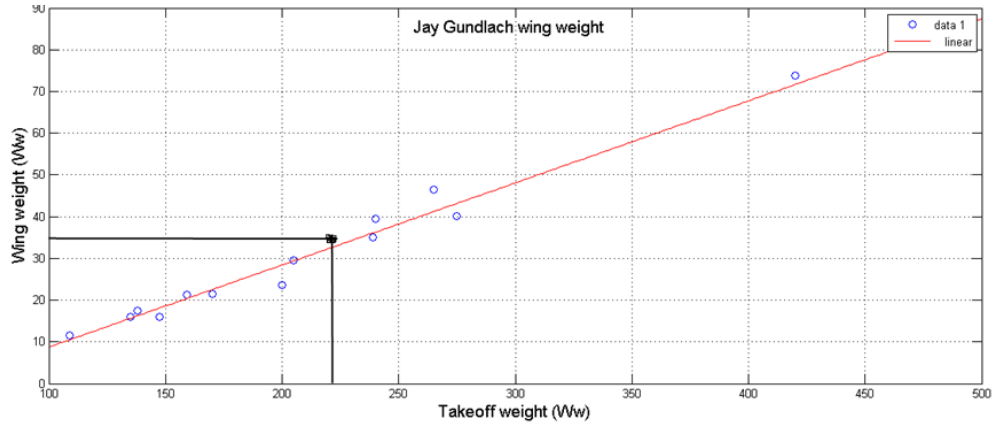


Figure (8) Gundlach wing weight estimation

Raymer equation for general aviation:

$$W_w = 0.036 \times S_w^{0.758} \times W_{fw}^{0.0035} \times \left(\frac{A}{\cos^2 \Lambda} \right)^{0.6} \times q^{0.006} \times \lambda^{0.04}$$

$$\times \left(\frac{100 \times t/c}{\cos \Lambda} \right)^{-0.3} \times (N \times w_{dg})^{0.49}$$

$$W_w = 0.036 \times 56.7^{0.758} \times 113^{0.0035} \times \left(\frac{8}{\cos^2 0} \right)^{0.6} \times 16.3^{0.006} \times 1^{0.04} \times$$

$$\left(\frac{100 \times 0.15}{\cos 0} \right)^{-0.3} \times (9 \times 220)^{0.49} = 33.85 \text{ kg}$$

$$33.85/128.7 = 26.3 \%$$

3.3 Derivation of new equation:

In this work a new formula is introduced to find wing weight estimation for TUAV's in conceptual design phase. This formula is derived from Gerard equation for sailplanes, but our formula shows more accurate

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results than Gerard for wing weight estimation. This formula is experimented by choosing randomly fifteen aircrafts wings parameters. The results from Figure (10) show that the fitting line slope gives the same wing weight fraction at both ends of the slope line which equals 14.2% W_w/W_o along the slope line from 100 kg up to 500 kg takeoff weight.

$$W_w = 0.03 \times (N_z \times w_o)^{0.826} \times A^{0.28} \times S_w^{0.19} \times (1 + \lambda)^{0.21} \times tc^{0.14};$$

$$W_w = 0.03 \times (9 \times 220)^{0.826} \times 8^{0.28} \times 5.27^{0.19} \times (1 + 1)^{0.21} \times 0.15^{0.14} = 34.52 \text{ kg}$$

This value represents 15.69 % of takeoff weight $\frac{W_w}{W_o}$, and 26.8 % of empty weight $\frac{W_w}{W_e}$.

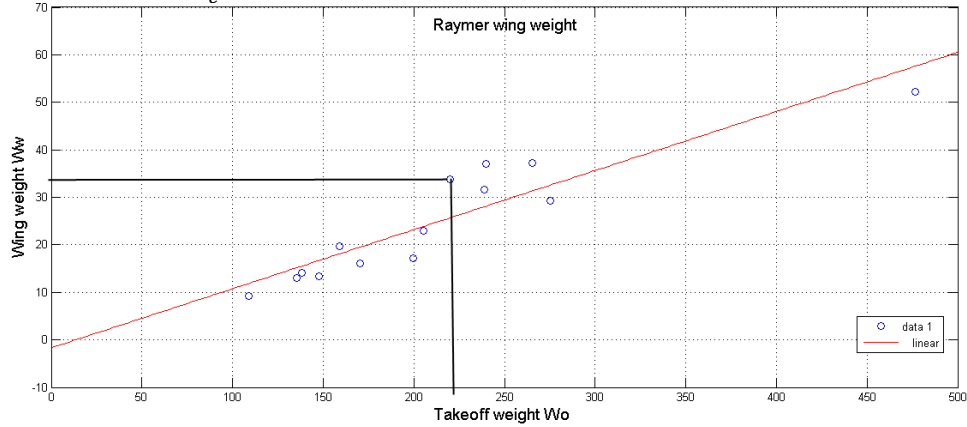


Figure (9) Raymer wing weight estimation

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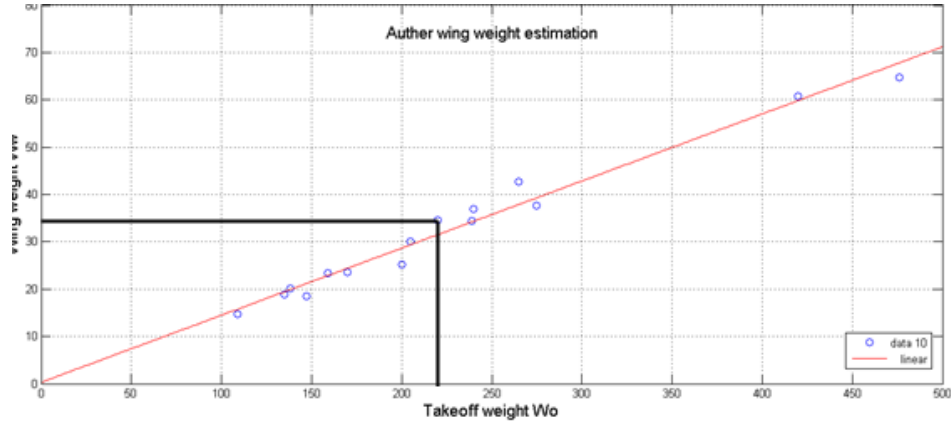


Figure (10) slop line of the new formula for wing weight estimation

4. Conclusion:

Various weight design formulas are applied to estimate wing weights of UAVs. Since these formulas are developed for manned aircrafts (which are much heavier than tactical UAVs) they sometimes give unacceptable estimations (to high values or to small values than it could be expected by common sense). Modification in coefficients of the available formulas is done in order to get better fit UAV design process. These modified formulas are the main contribution of this paper. Application of these formulas estimates more accurately wing weight of the UAVs.

Suggested formula for wing weight estimation is introduced:

$$Ww = 0.03 \times (N_z \times w_o)^{0.826} \times A^{0.28} \times Sw^{0.19} \times (1 + \lambda)^{0.21} \times tc^{0.14}$$

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